Specifications for the TE01 Signal Transmission of the Recycler Stochastic Cooling Systems

Gerald Jackson
Fermi National Accelerator Laboratory, P.O. Box 500, Batavia IL, 60510

May 4, 1998

1. Introduction

The Recycler ring is a storage ring designed to accumulate and cool a particle beam composed of antiprotons. Whereas the eventual method of emittance reduction will be electron cooling, the initial method will be stochastic cooling. It is therefore important to understand how to implement horizontal, vertical, and momentum cooling systems.

It turns out that the use of one of the two major normal arcs is necessary in order for a pickup electrode derived beam signal to cut a chord and meet the beam at the kicker electrodes. Because of the existence of obstacles on the MI-50 side of the Reycler, the MI-20 side was chosen.

2. Antiproton Considerations

For the horizontal and vertical cooling systems, the phase advance between the pickup and kicker must be an odd multiple of 90°. Since the phase advance per cell in the Recycler is 85.387° horizontally and 79.220° vertically, over approximately 35 half cells of distance the differential phase advance can be quite large. As it turns out, if the number of cells between the horizontal (vertical) pickup and kicker is 18 (17) cells, then the number of betatron oscillations between them is 4.27 (3.74). This corresponds to a horizontal (vertical) net phase advance of 97° (94°), more than close enough to obtain optimal cooling rates.

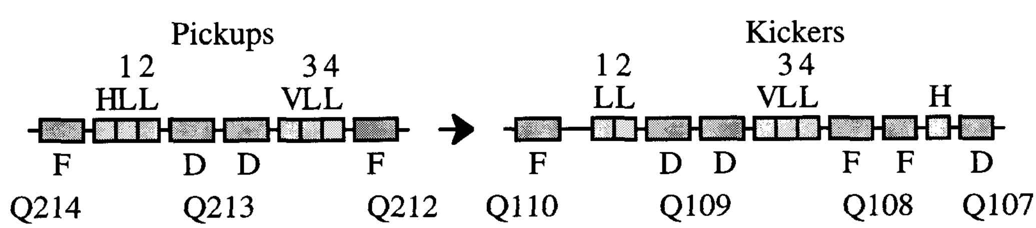

Figure 2.1: Geometry required to implement stochastic cooling in the Recycler ring.

Figure 2.1 shows the tank placement of the horizontal, vertical, and momentum pickup and kicker tanks to achieve the required relative betatron phase advance between the horizontal and vertical systems. There is 163.6 in. between the beam position monitors in the straight sections between pairs of normal arc gradient magnets. The pickup tanks are 54 in. long each. Therefore, three tanks just fit in each half cell.

The kinetic energy of the antiprotons is 8.000 GeV. Table 2.1 summarizes the kinematics of the antiprotons for the stochastic cooling systems. Note that the antiprotons travel about 0.5% below the speed of light, a significant amount given how close the signal transmission and beam propagation delays will be to one another.

Table 2.1: Kinematic considerations for the antiprotons in the Recycler ring.

Parameter	Value
Antiproton Kinetic Energy (GeV)	8.000
Antiproton Mass (GeV)	0.93827231
Antiproton Total Energy (GeV)	8.938
Antiproton Momentum (GeV/c)	8.889
Antiproton Relativistic Energy	9.52631
Antiproton Relativistic Velocity	0.994475
Speed of Light in Vacuum (m/ns)	0.29979246
Antiproton Velocity (m/ns)	0.29813614

3. Lattice Considerations

This region of the Recycler lattice is regular, with only the normal arc cell type (except for the horizontal kicker tank in a dispersion suppression cell). On the other hand, there are some injection devices which will limit the flexibility one may otherwise have placing tanks.

The most important limitation is the existence of the MI-22 transfer line and Lambertson. Aiming toward MI-30, the transfer line is terminated at the Lambertson just downstream of the gradient magnets over MIQ214 (between MIQ214 and MIQ215). Therefore, the most downstream position available for placement of a stochastic cooling pickup is the straight section between MIQ213 and MIQ214). The most upstream limit of the normal arc cell section is MIQ108, for a total of 17.5 cells. Since 18 cells are required in the horizontal plane, the horizontal kicker tank must reside in the first dispersion suppression cell. The length of available straight section in a dispersion suppression half cell is 102.1 in., too small for even two tanks.

The one big disadvantage of this geometry is that the horizontal pickup is only 11.6 m away from the injection Lambertson. This means that the horizontal pickup must have the full horizontal aperture of 3.8", which desensitizes the system dramatically. One option is to use a 4 electrode geometry for the horizontal pickup, which has no horizontal aperture restriction and a higher horizontal sensitivity.

Table 3.1: Downstream (proton direction) longitudinal coordinates of the pickup and kicker tanks in the Recycler. These numbers were lifted from the mechanical drawings generated by Terry Anderson for the vacuum system.

Parameter	Pickup	Kicker	Distance
Horizontal Tank Coordinate (ft.)	6601.152	8637.519	2036.367
Longitudinal #1 Tank Coordinate (ft.)	6605.652	8534.120	1928.468
Longitudinal #2 Tank Coordinate (ft.)	6610.152	8538.620	1928.468
Vertical Tank Coordinate (ft.)	6657.872	8586.340	1928.468
Longitudinal #3 Tank Coordinate (ft.)	6662.372	8590.840	1928.468
Longitudinal #4 Tank Coordinate (ft.)	6666.872	8595.340	1928.468

From mechanical drawings of the Recycler ring the beamline distance coordinates of the (proton direction) downstream end of each pickup and kicker tank can be determined. The data is presented in table 3.1 Plugging this information into the data shown in table 2.1, enough information exists to calculate the beam path distance between the pickup and kicker tanks of each of the four stochastic cooling systems. These distances are shown in table 3.2.

Table 3.2: Beam delay values for the actual Recycler geometry. The numbers in the table reflect the time for the beam to get from a given pickup tank to the conjugate kicker tank.

Parameter	Value
Feet per Meter Conversion	3.280839895
Horizontal Tank Distance (m)	620.685
Longitudinal #1 Tank Distance (m)	587.797
Longitudinal #2 Tank Distance (m)	587.797
Vertical Tank Distance (m)	587.797
Longitudinal #3 Tank Distance (m)	587.797
Longitudinal #4 Tank Distance (m)	587.797
Horizontal Distance (ns)	2082
Longitudinal #1 Tank Distance (ns)	1972
Longitudinal #2 Tank Distance (ns)	1972
Vertical Tank Distance (ns)	1972
Longitudinal #3 Tank Distance (ns)	1972
Longitudinal #4 Tank Distance (ns)	1972

4. Signal Transmission Geometry

Because the shortest distance is usually via a straight line, and because of surface obstacles which limit the placement of the path of the TE01 waveguide is placed, the waveguide falls on the chord between MIQ212/213 (proton direction upstream end of longitudinal pickup tank L4) and MIQ109/110 (proton direction downstream end of longitudinal kicker tank L1). The site coordinates for these quadrupoles are known and listed in table 4.1. Note that the typical grade elevation in this section of the ring is approximately 740'.

Table 4.1: Site coordinates for the Main Injector quadrupole centers which determine the signal transmission path for the Recycler stochastic cooling systems.

Parameter	MIQ212/213 (L4 Pickup)	MIQ109/110 (L1 Kicker)
Project Coordinate X (ft.)	98944.7645	99331.8605
Project Coordinate Y (ft.)	95423.481	97099.0968
Nominal Recycler Elevation (ft.)	720.5	720.5
Longitudinal Position (ft.)	6671.372	8534.120

The angle between this chord and the ring itself is calculated in table 4.2. The definition of angle is

$$\theta = \arctan\left(\frac{\Delta Y}{\Delta X}\right) \quad . \qquad (4.1)$$

Table 4.2: Calculation of the relative angles between the Recycler ring tangent and the chord at the two quadrupoles.

Parameter	MIQ212/213	MIQ109/110
Chord Angle (deg.)	257	257
Recycler Tangent Angle (deg.)	296	36
Relative Angle (deg.)	39	39
Cosine of the Relative Angle	0.77	0.77
Sine of the Relative Angle	0.64	0.64

Unlike the laser telescope approach to signal transmission, optical alignment is not necessary for TE01 waveguides. In fact, a radius of curvature of 20 m or greater has almost negligible effect on the attenuation of the signal across the chord due to mode-mixing phenomena. Therefore, terrain following a few feet below the surface (below the frost line) is sufficient for most of the distance. Figure 4.1 is an elevation view sketch of an optimum geometry in which all of the above criteria are met. Note that the distance penalty for the vertical rise and fall at the ends of the chord is a total of 8 ft.

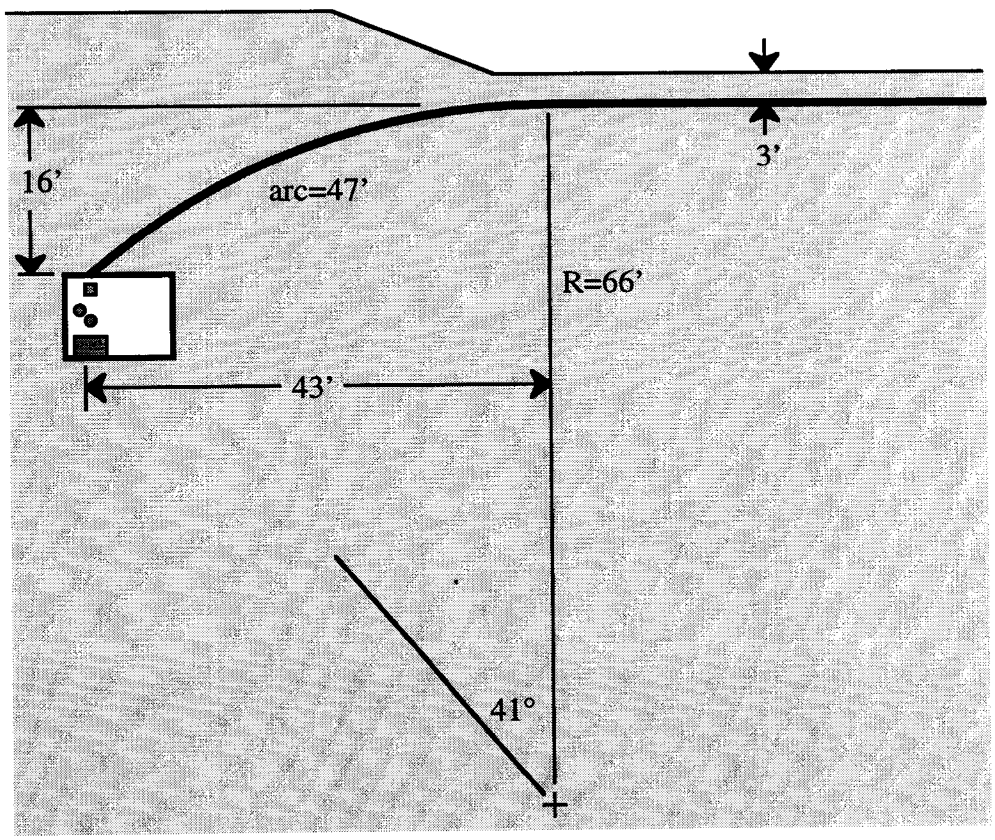

Figure 4.1: Sketch of the geometry used in signal delay calculations presented in this paper. This is the elevation view along the length of the chord between MIQ213 and MIQ109.

Figure 4.2 shows the plan view of the proposed TE01 waveguide geometry at each terminating quadrupole. The placement of the ends of the waveguide at the ends of the pickup and kicker tanks assures that there are no Recycler magnets in the way.. Therefore, the mode launchers and heliax cable connections have plenty of space, while these connections are in direct line with the cables from the pickup and kicker tanks for minimized signal delays.

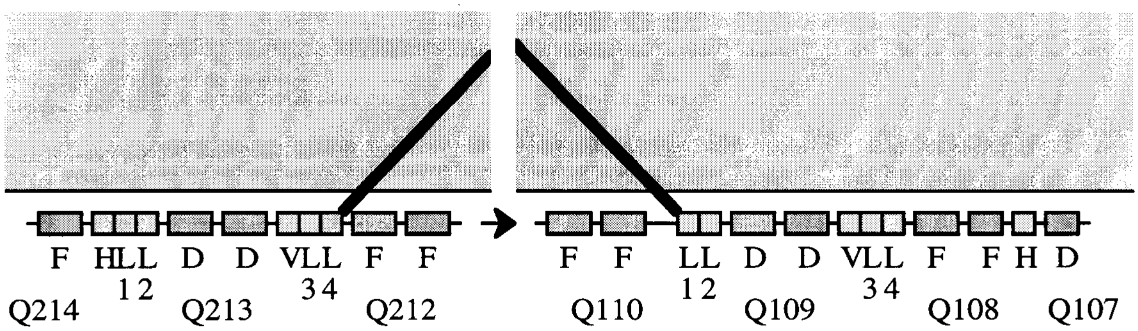

Figure 4.2: Plan view of the proposed conduit configuration between the laser telescope caves and the Recycler tunnel.

The group velocity of the signals in the TE01 waveguide is taken to be 98% of the speed of light. Taking into account the vertical deviation of the waveguide at the ends, table 4.3 calculates the delay of a signal following the TE01 waveguide.

Table 4.3: Length of the signal pathways along the chord between MIQ212/213 and MIQ109/110.

Parameter	Value
Distance between Waveguide Ends (ft)	1720
Signal Distance (ft)	1728
Signal Distance (m)	526.617
Waveguide Length of @ Light (ns)	1757
TE01 Signal Propagation (% light)	98
TE01 Signal Length (ns)	1792.5

Now the signal from the pickup has to get to the waveguide, and the signal from the waveguide has to get to the kickers. Following the beam path, the distances from the relevant quadrupole center to the FAR sides of the relevant tanks are listed in table 4.4. The far sides of the tanks were taken in order to be conservative. Other geometrical effects such as vertical cable paths to get to cable trays are included later.

Table 4.4: Distance between the relavant quadrupole on the chord and the **FAR** side of the pickup or kicker tank.

Parameter	Pickup	Kicker
Horizontal Tank Distance (ft.)	70.22	107.90
Longitudinal #1 Tank Distance (ft.)	65.72	4.50
Longitudinal #2 Tank Distance (ft.)	61.22	9.00
Vertical Tank Distance (ft.)	13.50	56.72
Longitudinal #3 Tank Distance (ft.)	9.00	61.22
Longitudinal #4 Tank Distance (ft.)	4.50	65.72

The propagation velocity in good coaxial cable is 88% of the speed of light. Therefore, the amount of delay per physical distance is calculated this propagation velocity. This velocity is calculated in table 4.5.

There are other delays in a stochastic cooling system. The laser transmitter and reciever each have a delay associated with them. Similarly, amplifiers, attenuators, switches, and delay trombones all have delays associated with them. Finally, it takes time for the signal generated on the pickup electrode (and the kicker signal delivered to the kicker electrodes) to get to (come from) the electrical port on the vacuum tank. Standard numbers quoted by Ralph Pasquinelli for each of these sources of delay are listed in table 4.6.

Table 4.5: Calculation of the signal delay in coaxial cable.

Parameter	Value
Speed of Light in Vacuum (m/ns)	0.299792458
Feet per Meter Conversion	3.280839895
Signal Speed in Coaxial Cable (c)	88%
Nanoseconds per Foot in Coax	1.16

Table 4.6: Miscellaneous delays in a standard stochastic cooling system.

Stochastic Cooling Component	Delay (ns)
Pickup Tank from Arrays to Port	5
Pickup Amplifiers and Trombones	5
Transmitttng Mixer	5
Miscellaneous Connecting Cables	15
Recieving Mixer	5
Kicker Electronics	5
TWT	15
Kicker Tank from Port to Arrays	5
Total	60

Adding together all of the delays, the total signal delay for each stochastic cooling system is listed in table 4.7. Note that these numbers represent fairly conservative numbers and could be shortened by a number of techniques if required. Also note that there is more than sufficient differential delay between the pickup and kicker to support stochastic cooling.

Table 4.7: Signal transmission delays in each of the 6 stochastic cooling systems for the Recycler ring. All delays are rounded up to the next integer number of nanoseconds.

Parameter	H	L1	L2	V	L3	L4
Miscellaneous Delays (ns)	60	60	60	60	60	60
TE01 Waveguide Delay (ns)	1793	1793	1793	1793	1793	1793
Pickup to MIQ213 Delay (ns)	82	76	71	16	11	6
MIQ109 to Kicker Delay (ns)	125	6	11	66	71	76
SubTotal	2060	1935	1935	1935	1935	1935
Beam Path Delay (ns) [from T.3.2]	2082	1972	1972	1972	1972	1972
Amount Signal Beats Beam (ns)	22	37	37	37	37	37